Flexible Integrated Silicon Photonic mm-Wave Frequency Upconversion Using GeSi EAMs

Laurens Breyne[1], Jochem Verbist[1,2], Jing Zhang[1], Piet Demeester[1], Gunther Roelkens[1], Guy Torfs[1]
[1]Ghent University-imec, Technologiepark 126, 9052 Ghent – Belgium
[2]Now with BiFast, Belgium
e-mail: Laurens.Breyne@ugent.be

ABSTRACT

With Radio-Over-Fiber becoming an established technology for the next generation mobile communication networks, interest in integrated microwave photonic circuits is rapidly increasing. Especially photonic frequency converters receive quite some attention as they offer a very large bandwidth and high isolation. In this work, a flexible, integrated silicon photonic upconverter employing GeSi EAMs is demonstrated. The circuit performs frequency upconversion of IF as well as IQ baseband signals to an RF carrier. OSSB signals can be generated when IF upconversion is performed. We demonstrate IF upconversion from 3.5 GHz to 24-28 GHz of 87.5 Mbaud to 200 Mbaud 16QAM and 50 Mbaud 64QAM. EVMs are within the requirements of the 3GPP standard [1].

Keywords: Photonic Upconversion, Microwave Photonics, Radio-over-Fiber, Silicon Photonics

1. INTRODUCTION

It has become clear that Radio-over-Fiber (RoF) will be an enabling technology for next generation mobile communication networks, e.g. 5G. While RoF is transitioning to an established technology, interest in integrated microwave photonics is rapidly increasing. Especially the photonic frequency up- and down-conversion is receiving quite some attention. Photonic mixers offer operation over a large frequency range, high isolation and immunity to electromagnetic interference. Several well-performing mixers already exist [2,3]. Furthermore, integrated photonic mixers can offer a very small form factor by avoiding large discrete components. Integration has been shown on various platforms [2,4,5]. Of the different technology platforms, silicon photonics (Si-Ph) is very attractive, as it offers low-cost fabrication, high scalability and dense integration. Low-loss waveguides, splitters, couplers, thermo-optic and PN-junction based phase shifters are easily integrated on Si-Ph Photonic Integrated Circuits (PICs). Next to the promising heterogeneous integration with III-V materials, the Si-Ph platform used for this work offers wafer-scale fabrication of SiGe Electro-Absorption Modulators (EAMs) and photodiodes [5].

In this paper, we demonstrate frequency upconversion from a 3.5 GHz IF signal to a 24-28 GHz carrier using GeSi EAMs. Analog transmission of 87.5-200 Mbaud 16QAM signals and 50 Mbaud 64QAM is shown with EVMs below 12.5% and 8% for 16QAM and 64QAM respectively. This is line with the 3GPP requirement [1]. The proposed structure allows not only for IF upconversion, but can also upconvert in-phase and quadrature baseband signals directly to RF. With some additional modifications, phaseshifters can be added to allow using the mixer in an optical beamforming network.

2. DESIGN AND IMPLEMENTATION OF THE PHOTONIC INTEGRATED CIRCUIT

The schematic of the PIC is shown in Fig. 1 (a). As input to the circuit, two laser lines are used. These can be derived from a mode-locked laser or can be generated by an MZM biased on its minimum transmission point. As such, the relative phase noise of the two laser lines can be controlled, which is crucial for RF operation. The circuit consists of two ring resonators and a more complex EAM-based modulator. The resonance wavelength λ_{res} of Ring 1 is tuned such that it coincides with λ_{res} of Ring 2. Furthermore, λ_{res} is set to coincide with one of the incident laser lines. The result will be that in Ring 1, one laser line passes through while the other line is dropped. The dropped line will be modulated by the EAM modulator structure. In Ring 2, the unmodulated and modulated laser line are combined. The combined signal can now beat on a photodiode to perform the actual frequency upconversion.

The modulating structure itself consist of two large parts: an MZM with a phase shifter and EAM in each arm, and a cascade of a phase shifter and a single EAM. The thermo-optic phase shifters (PSes) are only used for fixed phase shifts. By using a tunable power splitter, the to-be-modulated laser line can be sent through the EAM-MZM or the single EAM. When the laser line is sent through the single EAM, only amplitude modulation is possible. An IF signal should be supplied for upconversion to the desired RF frequency. If the laser line is sent through the EAM-MZM structure, several modulation schemes are possible:

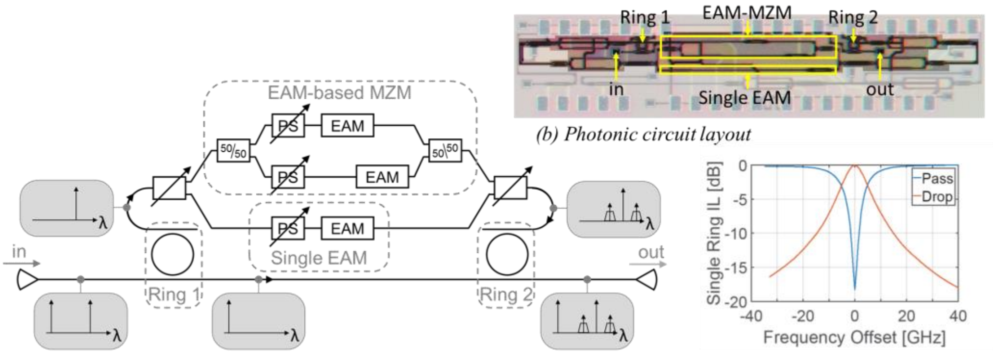
- The PSes are both set to 0°, the same signal is applied to the EAMs: this is the same as the single EAM structure.

- The top PS is set to 0° and the bottom one is set to 90°. The same IF signal is supplied to each EAM, but for the bottom EAM, a 90° phase shift (externally generated) with respect to the electrical IF carrier is added. This allows for optical single sideband (OSSB) modulation of the laser line.
- The top PS is set to 0° and the bottom one is set to 90°. Coherent modulation of the laser line is now possible. This allows to upconvert an in-phase and quadrature baseband signal directly to the desired RF-carrier by sending the in-phase and quadrature signals each to one EAM.

Other configurations are also possible, but not covered in this manuscript. For all described cases, the tunable power splitter was used in a binary mode: i.e all power was sent to the upper arm (EAM-based MZM) or lower arm (single EAM). Intermediate power splitting ratios are also possible to allow more flexibility, e.g. IQ and IF modulation or suppression of incident laser line. The annotated layout of the PIC is shown in Fig. 1 (b).

The measured transfer function of the pass and drop port of the rings is shown in Fig. 1 (c). A single ring has a free spectral range (FSR) of 4.1 nm, the full-width-half-max (FWHM) is 10.2 GHz, the extinction of the pass port and drop port is 19 dB and 29 dB respectively. The second ring limits the bandwidth of the IF or IQ-signal to its FWHM (10.2 GHz). Heaters are used to tune the resonance wavelength of the rings. If the resonance wavelengths of both rings are not perfectly aligned, the insertion loss will increase. It should be noted that there will be some leakage of the unmodulated laser line into the path for the modulated laser line. However, due to the cascade of the 2 rings, the contribution of this leakage term will be limited for sufficiently large spacings between both laser lines (e.g. > 20 dB isolation for spacings exceeding 15 GHz).

The PIC has been fabricated on imec's iSiPP50G Silicon Photonic platform. The EAMs are GeSi EAMs with a bandwidth > 50 GHz [5], the extinction ratio (ER) and insertion loss (IL) depend on the operating wavelength and biasing voltage. As the EAMs absorb some of the incident light, they can be used as monitoring photodiodes to set the resonance of Ring 1. To set the resonance of Ring 2, the photodiode used for the upconversion can be used as monitor. Low loss fiber grating couplers (FGCs) are used to interface the PIC with cleaved single mode fiber, each FGC has 4 dB loss at 1550 nm. The PIC as shown in Fig. 1 (b) measures 2.3x0.5 mm, including some additional teststructures.



(a) Photonic circuit schematic *(b) Photonic circuit layout* *(c) Ring characteristics*

Fig. 1(a): Schematic of the photonic circuit with annotated optical spectra. 50/50: 1-by-2 MMI, PS: phase shifter, EAM: electro-absorption modulator. (b) Annotated layout of the photonic circuit. The blanked out parts are bondpads and additional teststructures. (c) Transfer function of the drop and pass ports of the rings (frequency offset wrt the resonance wavelength).

3. MEASUREMENT SETUP AND RESULTS

As an experiment, a 3.5 GHz IF signal was upconverted to 24-28 GHz using the EAM-MZM, allowing single sideband communication. The full measurement setup is shown in Fig. 2.

To generate the two laser lines, a lithium niobate modulator is biased at its minimum transmission point and driven by a strong electrical signal (14 dBm). The balun is used to convert the single-ended signal from the signal generator to a differential signal to drive the dual-drive MZM in push-pull mode. In order to have an upconverted signal between 24 and 28 GHz, the frequency of the LO signal is chosen between 10.75 and 12.25 GHz (note that the IF signal is centered at 3.5 GHz and we use the upper sideband). With an optical input power of 13 dBm from the wavelength tunable laser (TLS), the resulting two laser lines each have an optical power of -5 dBm. As the MZM and the FGCs are polarization dependent, a polarization controller is placed before each of them. For simplicity, λ_{res} of Ring 1 is tuned to λ_{res} of Ring 2. In our case, this is around 1552.3 nm. The wavelength of the TLS is set such that one laser line is at λ_{res} The tunable splitter is set to send all power to the EAM-MZM. The top phase shifter is untouched, while the bottom phase shifter is set to 90°. The EAMs are biased at -1 V, the insertion loss is around 5 dB. The IF signal is brought to both arms using a 6-dB power splitter. The swing of the signal generator is chosen to minimize the EVM. A time delay (TD) is added to the electrical signal for the bottom EAM to generate a phase shift of 90° at 3.5 GHz, in order to generate the OSSB signal. The signal coming from the PIC is amplified by an EDFA and attenuated using a variable optical attenuator (VOA) to 8 dBm (the VOA allows to easily optimize the power incident on the photodiode). A 40 GHz photodiode with a responsivity of 0.6 A/W is used as receiver. The signal from the photodiode is amplified with a low noise amplifier (LNA) with 23 dB gain. An additional bandpass filter with a passband from 23.5-32 GHz is used to suppress any out-of-band spurs, this filter has 3 dB insertion loss. Before sending the signal to a real-time oscilloscope (RTO) for demodulation, an additional 24 dB amplifier is inserted to increase the received power level sufficiently above the RTO noise floor.

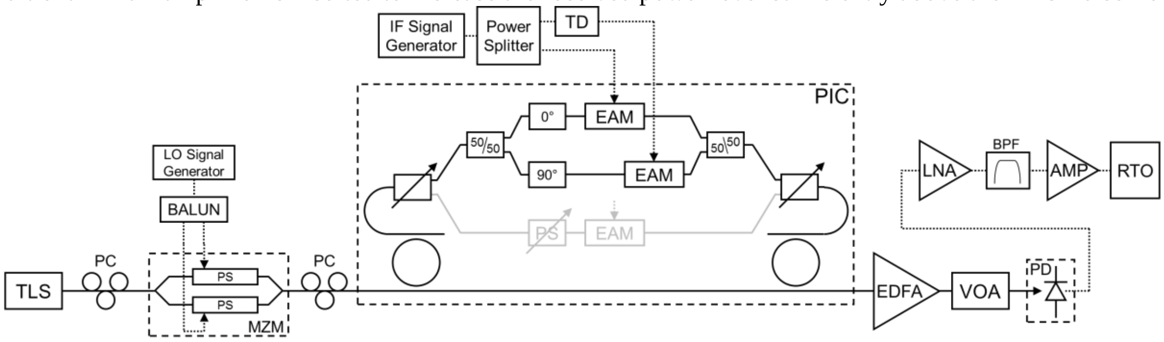
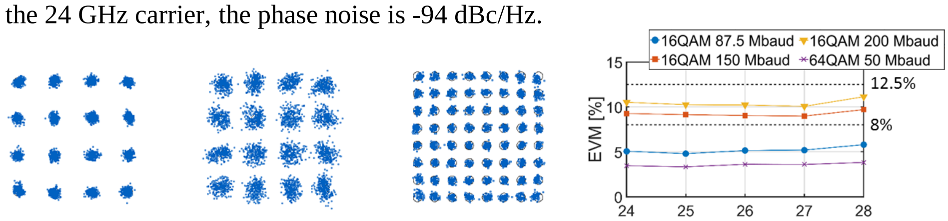


Fig. 2: Complete measurement setup. TLS: wavelength tunable laser source, PC: polarization controller, TD: electrical time delay, EAM: electro-absorption modulator, EDFA: erbium doped fiber amplifier, VOA: variable optical attenuator, LNA: low noise amplifier, BPF: bandpass filter, AMP: amplifier, RTO: real time oscilloscope

Without any signal applied to the EAMs, the power of the unmodulated and modulated laser lines before going into the EDFA is -14 dBm and -25 dBm respectively. In the described configuration (from IF Signal generator to RTO), the conversion loss measured using an IF of 3.5 GHz upconverted to 24 GHz is around 26 dB. Transmission experiments are performed where data on an IF of 3.5 GHz is upconverted to 24-28 GHz. For 87.5, 150 and 200 Mbaud 16QAM, the rolloff factor was 0.28 and the amplitude of the signals at the signal generator are 0.3, 0.46 and 0.5V respectively. The EVM was on average 5.2, 9.2 and 10.4 % respectively. For 50 Mbaud 64QAM, the EVM was on average 3.6%. The rolloff factor was 0.28, the signal amplitude was 0.32V. The 3GPP 5G NR standard requires that for the 24-28 GHz frequency band (n258), the EVM should be below 12.5% and 8% for 16 and 64QAM respectively [1]. These requirements are fulfilled over the complete band. The OSSB modulation scheme results in approximately 15 dB suppression of the lower sideband compared to the upper sideband. The phase noise was measured when upconverting a 3.5 GHz sine wave to 24 GHz using an LO of 10.25 GHz. At 100 kHz offset from the 24 GHz carrier, the phase noise is -94 dBc/Hz.



(a) 87.5 Mbaud 16QAM at 25 GHz

(b) 200 Mbaud 16QAM at 25 GHz

(c) 50 Mbaud 64QAM at 25 GHz

(d) EVMs for various baudrates, constellations from 24 to 28 GHz

Fig. 3: (a)-(c): Constellation diagrams for various baudrates and constellation at an RF carrier of 25 GHz. (d): EVM at 24-28 GHz for various baudrates and constellation diagrams. The 3GPP specifications [1] requires the EVM for 16QAM and 64 QAM to be below 12.5 % and 8 % respectively.

4. CONCLUSION

We have demonstrated a flexible, integrated silicon photonic upconverter using GeSi EAMs. Altough not shown, the structure can also directly upconvert an in-phase and quadrature baseband signal to an RF carrier. Upconversion of a 3.5 GHz IF signal to an RF frequency of 24-28 GHz is shown for 87.5-200 Mbaud 16QAM and 50 Mbaud 64QAM, with EVMs within the specifications for the 3GPP NR standards [1], i.e. below 12.5% and 8% for 16QAM and 64QAM respectively.

ACKNOWLEDGEMENTS

This work was supported by the UGent Special Research Fund (BOF) and the ERC Advanced Grant 695495: “ATTO, A new concept for ultra-high capacity wireless networks”.

REFERENCES

[1] 3GPP TS 38.104: “NR; Base Station (BS) radio transmission and reception,” V15.4.0, 2018-03

[2] E. Chan et al, "Microwave Photonic Downconverter With High Conversion Efficiency," in *JLT 2012*

[3] T. Jiang et al, "Microwave photonic phase-tunable mixer," in *OE 2017*

[4] S. Jin et al, "RF Frequency Mixer Photonic Integrated Circuit," in *PTL 2016*

[5] K. Van Gasse et al, "Silicon Photonics Radio-Over-Fiber Transmitter Using GeSi EAMs …," in *PTL* 2019.